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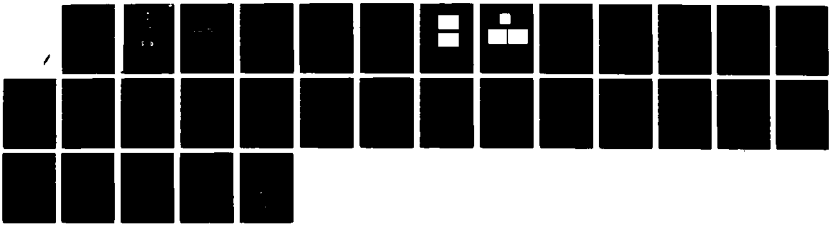

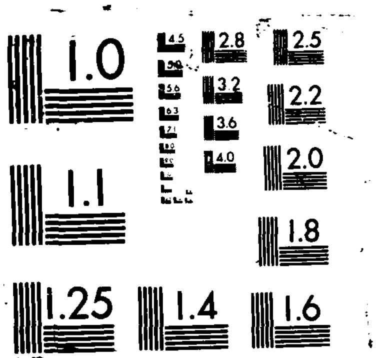
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DEFENCE RESEARCH ESTABLISHMENT OTTAWA
REPORT NO. 958

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ABSTRACT

This report gives the results of measurements of the response of some commercial photodiodes and particle detectors to monoenergetic gamma-ray sources. The absolute response and the response, as a function of photon energy, detector thickness and discriminator level, were investigated and are shown to be in general agreement with earlier calculations. It is concluded that, with appropriate photon filtration, the small photodiodes tested would be suitable for the relatively high dose-rate measurements of primary interest for military applications, although their thickness is greater than the thickness for best energy response.

RÉSUMÉ

Nous vous donnons dans ce rapport, les résultats des mesures du rendement de certaines photodiodes commerciales et de détecteurs de particle face aux rayons gammas monoénergétiques. Après avoir analyzé le rendement absolu et le rendement en fonction de l'énergie des photons, l'épaisseur du détecteur et le niveau des discriminateur, nous nous apercevons que nos mesures concordent, en général, avec les calculs antérieurs. Nous concluons donc qu'en utilisant une filtration appropriée des photons, les petites photodiodes testées, même si l'épaisseur est plus grande que celle qui donne le meilleur rendement énergétique, sont adéquates pour les mesures à taux d'irradiation élevé lequel est primordial pour les applications militaires.

1. Introduction

Silicon radiation detectors offer advantages in reliability, size and cost over ion chambers and Geiger tubes as the detectors for many radiation-measuring instruments. A general requirement for these instruments is uniform energy response for gamma energies above 80 keV. Calculations using radiation-transport codes (McGowan (1)) have shown that, at least in theory, responses can be obtained which are sufficiently energy independent for most practical purposes. General agreement was found between the calculated responses and a limited number of experimental values. In a more recent report (McGowan (2)), calculated responses were compared with measured responses of an Ortec particle detector to ^{141}Ce gamma rays having an energy of 145 keV. The effects on the detector response of scattering bodies and of layers of copper and tin next to the detector were also discussed in that report.

The calculated responses of Ref (1) apply to thin (in length) cylindrical detectors with selected adjacent materials usually silicon (aluminum is essentially equivalent at most gamma energies). These conditions are fairly well met for measurements made here with Ortec particle detectors, sandwiched between layers of aluminum, so that the measured responses should be comparable to the calculated values.

Also investigated in this report are the energy responses of some RCA photodiodes. Of particular interest, are photodiodes C30807 and C30808 since their quality and size make them suitable as sensors for high-range military dose-rate meters. The count rates from larger detectors cannot be handled readily at the largest dose rates (up to 10 gray/hour) required to be measured by military dose-rate meters. The diameter/thickness ratios for the smaller photodiodes are not very large and the sensitive areas tend to diverge from the areas defined by the doping of the front surfaces. Evidence of this arises from the increase in measured area observed as the depletion thickness is increased with applied electric field. These measurements were made by comparing the counts from ^{241}Am gammas with a lead aperture of known area in front of the detector with the counts when the aperture was removed. Furthermore, the photodiodes are permanently mounted so that the material adjacent to the back surface cannot be selected. Thus, the energy response of these detectors may deviate significantly from the calculated results.

2. Experimental Methods

The detector bias voltage was applied using a 10-Mohm resistor in series with a variable battery supply. (Power supplies operated from the 115-V ac mains were avoided since these were frequently found to introduce noise pulses). Because of the low currents in these detectors, only a small fraction of the applied voltage was across this resistor. The charge pulses induced by photons interacting with the detectors were fed into a charge-sensitive preamplifier which used a bipolar FET as a source follower in the input stage. The preamplifier used a feedback capacitor of approximately 0.5 pF, giving output pulses of approximately 90 μV/keV for energy absorbed in the detector.

The preamplifier pulses were amplified and shaped with time constants of approximately 1 μs, using an Ortec 410 amplifier, before being analysed with an Ino-Tech IT-5300 pulse-height analyser. Energy calibration of the system relied on the absorption peaks of the lower-energy monenergetic sources and was checked frequently using the 59.5-keV ^{241}Am source. The dose rates were kept small enough so that dead-time corrections were small.

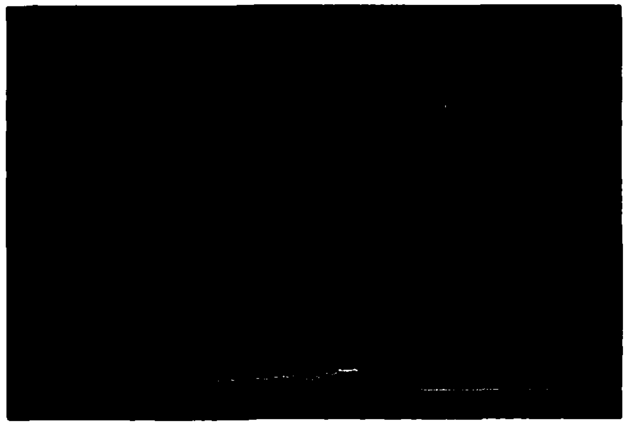
The gamma sources used for these measurements were ^{241}Am, ^{141}Ce, ^{133}Ba, ^{137}Cs and ^{60}Co with effective energies of 0.0595, 0.145, 0.35, 0.66 and 1.25 MeV, respectively. The ^{133}Ba source emits a photon at 0.356 MeV, which accounts for a large fraction of its dose, and gammas with lesser intensities at 0.384, 0.303, 0.276 and 0.081 MeV. This source was used with a 2-mm tin filter which removed most of the 0.081-MeV gammas. Otherwise, this peak would predominate because of the relatively high absorption cross section for silicon at that energy. The above effective energy of 0.35 MeV is with the tin filter in use.

The ^{60}Co and ^{137}Cs sources were used both in their open positions and with lead attenuators which reduced the exposure by ten times for the ^{60}Co and seventy five times for the ^{137}Cs. The most important difference in the quality of the radiation between the open and attenuated sources is the presence of the backscatter component from the lead containers of the open sources. This gives a component of radiation which has an energy of about 200 keV.

As in Ref (2), the ^{141}Ce source was used with a 1/2-mm copper filter which effectively removed the 37-keV x-rays.

The source strengths for the ^{60}Co and ^{137}Cs sources were taken from tables, based on NRC calibrations, giving exposures in Roentgens (R), while the source strengths of the ^{241}Am, ^{133}Ba and ^{141}Ce sources were measured using air ionization chambers. Rad/R (or cGy/R) ratios of 0.929 and 0.955 were used for the ^{241}Am and ^{141}Ce sources, respectively, and 0.957 was used for the other three sources.

(a)



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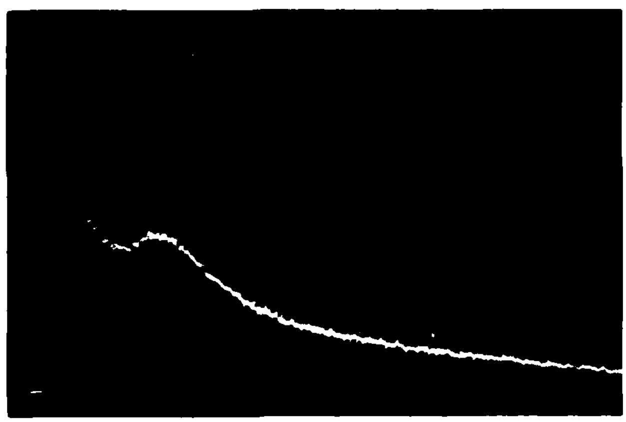
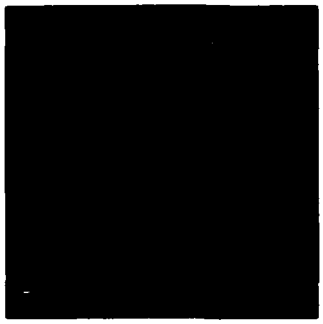
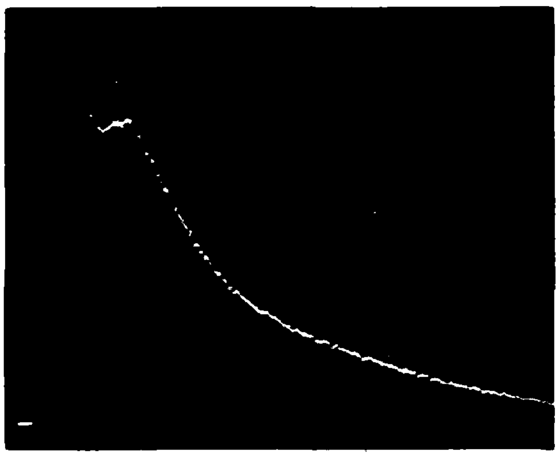


Figure 1. Pulse-height spectra taken with an RCA C30807 photodiode. The cursor (vertical dotted line) is at channel 100 (about 52 keV) for both spectra. (a) ^{241}Am source. The 59.5-keV peak is seen centred at channel 115 with a resolution of about 4 keV (FWHM). Noise and Compton-electron pulses are seen between channels 13 (the analyser discriminator level) and 15. The peak at about 21 keV may be due to x-rays produced in the gold plating of the photodiode package. (b) ^{60}Co source. This detector is much too small to show the photopeaks (1.17 and 1.33 MeV) for this source and 90% of the pulses are less than 200 keV. The broad peak between 50 and 65 keV is due to Compton electrons traversing the detector and producing pulses characteristic of the detector thickness.



(a)



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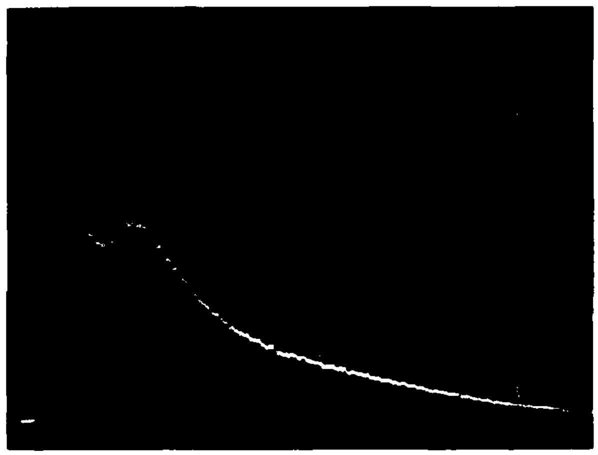

(c)

Figure 2. Pulse-height spectra taken with Ortec particle detector #1 (see Table 1) operating with 40-V bias. (a) ^{241}Am source. The 59.5-keV peak is centered at channel 60 and is seen to be much broader than for the small photodiode in Fig. 1, having a resolution of about 11 keV (FWHM). (b) ^{60}Co source, unattenuated. This spectrum is similar to that for the photodiode in Fig. 1 but there is a larger fraction of large pulses (about 75% are below 200 keV) and the peak occurs at a higher energy (between 95 and 100 keV) because of the greater thickness of this detector. (c) ^{60}Co source, attenuated by a factor of 10. The peak in this spectrum is more pronounced than for the open (unattenuated) source because of the reduction in backscattering from the source container. This backscatter component consists of photons of energy about 200 keV and increases the response in terms of counts per unit dose by about 5%.

3. Pulse-Height Spectrum

On accumulation of pulses from the exposed detectors, pulse-height spectra are generated as illustrated in Fig 1 and Fig 2. Fig 1a shows a ^{241}Am spectrum using a C30807 detector (area 1.5 mm^2). The well-defined 59.5-keV peak is seen about 15 channels to the right of the cursor (the vertical dotted line which is at channel 100). No counts are observed in channels 1 to 13 because of the discriminator setting of the analyser. Noise and Compton-electron pulses larger than this setting are observed in channels 15 to 25. Above channel 25 which corresponds to about 12 keV, most of the counts are due to the radiation. The peak at about 21 keV is undefined. It is not due to photons of this energy from the source as it is not reduced relative to the main peak by copper filtration. It may result from x-rays generated in materials, such as gold, near the detector.

For higher energies the pulse height is greatly limited by the detector dimensions, since the ranges of most of the Compton electrons and the photoelectrons exceed the detector thickness. Fig. 1b is a pulse-height spectrum from the same detector as Fig 1a using an open ^{60}Co source. The broad peak which is observed between 50 and 65 keV is due to Compton electrons traversing the detector. The energy of this peak is an indication of the detector thickness.

Fig 2a shows the pulse-height spectrum from a 60-mm^2 particle detector using the ^{241}Am source. Note the broader 59.5-keV peak than for the smaller (less noisy) detector in Fig 1a. The discriminator level has been increased from that of the smaller detector and noise pulses are seen as a peak at about 22 keV.

Fig 2b and Fig 2c are pulse-height spectra from the same detector as for Fig 2a using a ^{60}Co source. Broad peaks are seen between 85 and 110 keV. The higher energy of this peak relative to that of Fig 1b indicates that this detector is thicker than the C30807 used above. The spectrum of Fig 2b was recorded using the open ^{60}Co source whereas that of Fig 2c is from the same source but with a lead attenuator which reduced the radiation field by a factor of ten. The main difference in the shapes of the two spectra is the relatively larger number of pulses below the valley (at about 75 keV) in the "open" spectrum. This is attributed to the presence of backscattered photons (of energy approximately 200 keV) from the source container, which produce low-energy Compton electrons but which are removed by the attenuator. Changes in the source spectrum by buildup in the attenuator may also alter the detector response to some extent.

4. Response of Detectors

The detector response in terms of counts per unit area and per unit dose depends primarily on the sensitive thickness τ and the discriminator level (or cut-off energy E_c) below which all pulses are rejected. For E_c set to reject noise pulses but below the 59.5-keV peak, the response to ^{241}Am photons is expected to be directly proportional to τ as long as τ is much larger than the 59.5-keV photoelectron range of 30 μm in silicon. However, for photons which produce Compton electrons and photoelectrons of range much greater than τ, such as ^{60}Co gammas, the response is less dependent on τ. Thus, the response ratio between two detectors depends on the radiation source.

4.1 Determination of Detector Dimensions

The areas of the particle detectors are defined by the areas of gold evaporated on the front surfaces and the areas of the photodiodes are determined by front surface doping. As these areas were not always well defined visually, the effective areas were determined from the responses with and without apertures, using either the ^{241}Am gamma source or an alpha-particle source.

As the applied voltage on these detectors is increased they become depleted of majority carriers starting at the front (gold) surface, the depleted thickness increasing with voltage until they become fully depleted (thickness τ_{max}) in the case of a high-quality detector. Only the depleted portion is effective as a radiation detector. Thus, the effective τ of the detectors depends on the applied voltage, and several of the detectors were used with more than one value of τ. The effective area of the detectors, as measured by the ^{241}Am gamma source, tends to decrease as τ is decreased below τ_{max}. Response measurements are calculated in this report using the effective area for τ_{max}.

4.2 Ortec Surface-Barrier Detectors

These detectors were purchased as having nominal areas of 50 mm^2. Two were designated as being totally depleted at specified voltages, while the others were assigned minimum depletion depths at specified voltages. The effective areas, measured for each detector at the largest applied voltage, are listed in Table I. These values, which were used in calculating detector responses, are seen to be somewhat greater than the nominal area. The τ_{max} values, measured with a micrometer, are also listed along with the manufacturer's τ_{max} for the two totally-depleted detectors.

A summary of the responses of these detectors to ^{60}Co and ^{241}Am gamma rays is given in Table I for counts above the discriminator level of 40 keV. Responses are shown for several applied voltages for some of these detectors. Variation (with voltage) in the response to the low-energy ^{241}Am gammas is a good indication of the variation in the sensitive thickness τ of the detector. Comparison of responses to those of the totally-depleted detectors indicates that all of the other detectors are close to being totally depleted at the maximum voltages used.

The response to the ^{60}Co gammas is seen to be less dependent on detector thickness than the response to ^{241}Am. This is a result of the relatively large range of the Compton electrons from ^{60}Co which is much greater than τ for these detectors. Measurements were made both with a relatively open ^{60}Co source and with the same source with lead attenuation. The backscatter component (at about 200 keV) of the open source results in an enhanced response which is found to be about 5% greater than with the attenuated source. (Calculations (Ref (1)) show the response at 200 keV to be approximately double that at 1.25 MeV depending on detector thickness).

Responses, calculated in Ref (1) using the computer code CYLTRAN, are included in Table I. Accurate comparisons between the measured and calculated values cannot be made because of uncertainties in the detector dimensions, particularly the effective thickness, but the measured responses to ^{60}Co for the thicker detectors are seen to be greater than the calculated values. This is probably due to the presence of some scattered photons for both the open and attenuated sources. In practical situations, there are probably always enough secondary photons present to significantly alter the detector response. For energies above 1 MeV, this means that the detector response is effectively somewhat greater than the theoretical value.

As discussed in Sec 3 the ^{60}Co pulse-height spectra from these detectors have a peak which occurs at an energy which depends on detector thickness τ. The correlation between the energy of this peak and the detector thickness (or the response to ^{241}Am gammas) can be seen in Table I. In addition to the increase in energy with τ, these peaks become broader and less defined as τ increases.

A valley or minimum in the pulse-height spectrum is also observed below the spectrum peak. Slight minima are predicted by the calculations for the thicker detectors, but the minimum observed experimentally is determined in part for these detectors by the presence of noise pulses in the lower part of the spectra. These result in the occurance of a valley at some energy above that predicted for a noise-free detector.

TABLE I

Response of Ortec Surface-Barrier Detectors to ^{60}Co and ^{241}Am

Gamma Rays for a Discriminator Setting Ec of 40 keV

Detector #	Applied Voltage (V)	Measured Area (mm^2)	Thickness Measured (μm)	Thickness Stated (μm)	Response (10^7 Counts/(mm^2Gy)) ^{241}Am	Response ^{60}Co (Open)	Response ^{60}Co (Pb)	Response Ratio $^{241}Am/^{60}Co$ (Open)	Response Ratio $^{241}Am/^{60}Co$ (Pb)	Energy (keV) of ^{60}Co Valley	Energy (keV) of ^{60}Co Peak
1	100	57	310		32		2.24		14	78	97
1	40				30	2.38	2.25	12.5	13	80	95
1	10				15		1.55		10	41	55
2	100	68	310		30						
2	100				26	1.93		13.5		75	95
2	45				18	1.62		10.5		46	72
2	25				13	1.48		9		36	54
2	10				9	1.29		7			
3	80	61	280		26		2.00		13	62	86
3	40				18		1.72		10.5	48	65
3	12				10		1.30		8		
4	100	60	230	236	25	1.97		13		54	68
5	100	54	170	157	18	1.64		11		35	62
6	60	55	150		17	1.51		11		31	45
6	20				13	1.50		9		36	43
Calculated in	Ref (1)			500	45		2.11		21.4		170
"	"			300	27.1		1.77		15.3	65	110
"	"			200	17.8		1.54		11.6	40	70
"	"			150	13.6		1.33		10.2	30	50
"	"			100	8.9		1.00		8.9	17	38
"	"			50	4.4		0.52		8.4		20

TABLE II

Response in Units of 10^7 Counts/(mm^2Gy) of Ortec Detector #1 to Various Photon Sources at Applied Voltages of 100, 40 or 10 V as a Function of Discriminator Setting Ec

Source, Energy (MeV)	^{241}Am, 0.06			^{141}Ce, 0.145		^{133}Ba, 0.35	^{137}Cs, 0.66		^{60}Co, 1.25			
Filtration	2 mm Al			1/2 mm Cu		2 mm Sn	Pb (÷ 75)		Pb (÷ 10)			Open
Applied Voltage (V)	100	40	10	100	10	100	100	10	100	40	10	40
Ec (keV)												
30	35	33	-	7.7	-	4.29	3.13	-	2.40	2.43	-	2.63
40	32	30	15	5.1	2.63	3.67	2.84	1.73	2.24	2.25	1.55	2.40
50	29	27	12	2.81	1.53	3.18	2.66	1.55	2.08	2.10	1.37	2.22
60	14	13	6	1.86	0.94	2.82	2.38	1.37	1.95	1.97	1.17	2.08
80				1.26	0.59	2.14	2.02	1.12	1.76	1.75	0.92	1.80
100				0.89	0.42	1.49	1.88	0.91	1.50	1.52	0.73	1.54
125				0.57	0.23	1.13	1.44	0.71	1.24	-	0.59	-
150						0.71	1.21	0.55	1.04	1.02	0.47	1.02
200						0.16	0.84	0.30	0.74	0.71	0.30	0.70

With Added Filtration of 4 kg/m^2 (0.4 g/cm^2) Sn

Attenuation Factor Used	0.080			0.805		0.970	0.986		0.990		
40	2.7	2.5	1.3	4.1	2.12	3.56	2.80	1.71	2.21	2.23	1.53
60	1.2	1.1	0.5	1.50	0.76	2.73	2.35	1.35	1.93	1.95	1.16
100				0.72	0.34	1.45	1.85	0.90	1.49	1.50	0.72

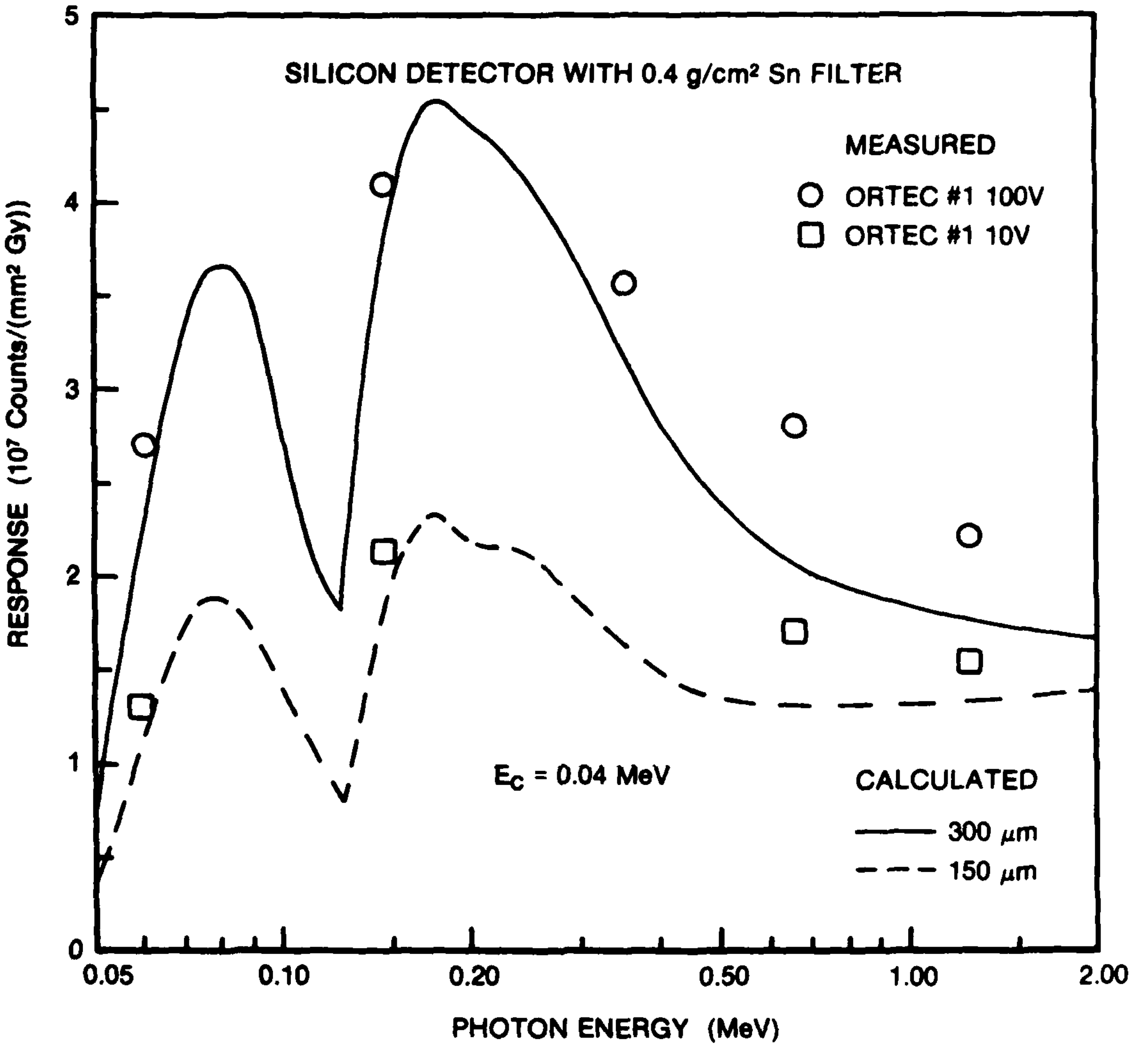

Figure 3. Response of an Ortec particle detector as a function of photon energy for the pulse-hight discriminator set at 40 keV. The two bias voltages for the one detector result in two effective thicknesses. The experimental points for five monoenergetic gamma-ray sources are compared with curves calculated in Ref (1). The measured responses with 100 V are somewhat larger than the calculations predict for the measured maximum thickness of 310 μm. The filtration is applied using accepted attenuation factors for tin.

More detailed response-measurement results are given in Table II for detector 1 of Table I. Measured values are listed for the five sources used with the filtration shown. Further filtration of 0.4 g/cm^2 of tin was applied by calculation using the attenuation factors for tin at the principal energy peaks of these sources. As shown in Ref (1), this amount of tin shielding significantly improves the energy response of silicon detectors. The measured responses are compared in Fig 3 with calculated responses for 300- and 150-μm detectors. Values for Ec = 40 keV are used in order to make realistic comparisons for the ^{241}Am and ^{141}Ce sources. The measured energy responses conform fairly well to the shape of the calculated curves though the measured responses to the ^{137}Cs source are relatively high. The responses measured at 100 V are somewhat higher than would be predicted for a 310 μm detector (310 μm is the measured thickness). The relatively large measured responses at ^{60}Co and ^{137}Cs energies can be accounted for in part by the fact that these are not purely monoenergetic sources; these radiation fields contain significant fractions of scattered photons of lower energies where the response is greater. At 10 V this detector response is above the curve calculated for a 150-μm detector indicating a thickness greater than that value.

4.3 RCA Photodiodes

The sensitives of three RCA photodiode types (C30807, C30808 and C30809) were measured using the various photon sources. A C30812 was also checked with ^{241}Am and ^{60}Co. The effective area was measured for one diode of each type and used for all diodes of that type. These areas are listed in the tables of response for these photodiode detectors. The thicknesses of these detectors could not be measured as they are cemented directly to their transistor cans.

A summary of responses to ^{241}Am and ^{60}Co is given in Table III for the smallest of these photodiodes C30807. All of these detectors were found to operate well with 20 and 40 V inverse bias, typical resolution for the ^{241}Am gamma being 5 keV (FWHM) at room temperature. Increases in ^{241}Am response with increasing bias from 20 to 40 V were from 10 to 20% with the exception of detector 7-10 which showed an increase of about 50%. Thus, with the possible exception of 7-10, these detectors appear to be fully depleted at 40 V. A bias of 20 V is not large enough to assure operation of some of these detectors near their maximum sensitivity.

Excluding detector 7-1, the remaining six detector responses to ^{241}Am are seen to be within 10% of the average value of 16.3 x 10^7 counts/(mm^{2}Gy) when operated at 40 V. Again excluding 7-1, the four values of the response to the attenuated ^{60}Co source are within 7% of the average value of 1.71 x 10^7 counts/(mm^{2}Gy). The responses to the open ^{60}Co source are seen to be about 4% higher than for the attenuated source. The reason for this discrepancy is discussed above for the ORTEC detectors.

TABLE III

Response of RCA Photodiodes Type C30807 to ^{60}Co and ^{241}Am Gamma Rays for a Discriminator Setting Ec of 40 keV. The Measured Area of These Detectors is 1.5 mm^2.

Detector #	Applied Voltage (V)	Response (10^7 Counts/(mm^2Gy)) ^{241}Am	Response ^{60}Co Open	Response ^{60}Co (Pb)	Response Ratio $^{241}Am/^{60}Co$ Open	Response Ratio $^{241}Am/^{60}Co$ (Pb)	Energy of ^{60}Co Spectrum Valley (keV)	Energy of ^{60}Co Spectrum Peak (keV)
7-7	60	18.6	2.00	1.91	10.0	10.5	43	60
7-1	40	20.1	1.94	1.83	9.1	9.7	38	63
7-10	40	17.7		1.75		10.1	32	49
7-7	40	17.6						
7-8	40	16.5					24	47
7-6	40	15.9	1.70	1.65	9.4	9.6		41
7-3	40	15.2	1.66	1.61	9.2	9.4		
7-11	40	14.9						
7-1	30	20.1						
7-10	30	15.4	1.82		8.5		41	55
7-1	20	16.9						
7-7	20	15.7						
7-4	20	15.0	1.68		8.9			46
7-6	20	14.5						
7-2	20	14.1	1.57		9.0			44
7-8	20	13.9						
7-3	20	13.6	1.33		10.2		26	40
7-11	20	13.4						
7-10	20	11.5	1.66	1.56	6.9	7.4	35	50
7-8	15	11.8						
7-7	10	12.1		1.43		8.5	30	42
7-11	10	11.4						
7-10	10	8.5	1.52		5.6		28	35
7-3	05	9.2	1.21		7.6		23	33
7-10	05	6.8	1.18	1.11	5.8	6.1	18	31

TABLE IV

Measured Response of Photodiode 7-10 in Units of 10^7 Counts/(mm^2 Gy)

as a Function of Discriminator Level Ec at Bias Voltages of 40,20 and 5 V

Source, Energy	^{241}Am, 0.06 MeV			^{137}Cs, 0.66 MeV						^{60}Co, 1.25 MeV					
Filtration	2 mm Al			Open			Pb(÷75)			Open			Pb (÷10)		
Applied Voltage	40	20	5	40	20	5	40	20	5	40	20	5	40	20	5
Ec (keV)															
20	27.2	21.3	12.4	2.42	2.16	1.72	2.33	2.19	1.68	2.31	2.06	1.70	2.14	1.92	1.60
30	21.0	14.9	8.8	2.17	1.90	1.42	2.11	1.89	1.41	2.11	1.85	1.41	1.96	1.74	1.34
40	17.7	11.5	6.8	1.98	1.70	1.16	1.94	1.72	1.20	1.94	1.66	1.18	1.83	1.56	1.11
50	13.4	9.3	5.0	1.81	1.52	0.97	1.79	1.56	1.03	1.79	1.47	1.00	1.69	1.40	0.92
60	4.9	2.4	1.3	1.65	1.36	0.84	1.66	1.40	0.82	1.62	1.29	0.86	1.54	1.23	0.79
80				1.38	1.09	0.61	1.41	1.15	0.70	1.33	1.02	0.63	1.26	0.98	0.58
100				1.15	0.88	0.45	1.19	0.93	0.49	1.10	0.83	0.46	1.06	0.81	0.43
125				0.93	0.68	0.31	0.97	0.80	0.33	0.89	0.64	0.31	0.86	0.63	0.30
150				0.74	0.50	0.21	0.78	0.54	0.22	0.72	0.49	0.20	0.70	0.49	0.21
200				0.45	0.26	0.10	0.48	0.25	0.08	0.47	0.28	0.08	0.47	0.29	0.10
With Added Filtration of 4 kg/m^2 (0.4 g/cm^2) Sn															
Attenuation Factor Used		0.080						0.986						0.990	
40	1.42	0.92	0.54				1.91	1.70	1.18				1.81	1.54	1.10
60	0.39	0.19	0.10				1.64	1.38	0.81				1.52	1.21	0.78
100							1.17	0.92	0.48				1.05	0.80	0.43

The response of detector 7-10 is given in more detail for the ^{241}Am, ^{137}Cs and ^{60}Co sources in Table IV. These detectors were sufficiently noise free to permit discriminator settings at least as low as 20 keV without introducing errors due to noise pulses. Measurements were not made with these small-area detectors and the ^{141}Ce or ^{133}Ba sources as these were low-level sources which gave poor counting statistics.

A summary of responses of the C30808, C30812 and C30809 detectors to ^{241}Am and ^{60}Co is given in Table V. The C30808 and C30809 detectors appear to be fully depleted at 40V with the possible exception of 8.2. The C30812 detector is much thicker and requires a larger bias for full depletion.

At 40V, the ^{241}Am response of detectors 8-1 to 8-4 are within 5% of the average value of 16.2×10^7 counts/(mm^{2}Gy). Detector 8-5 is from a batch of C30808s purchased after the 8-1 to 8-4 measurements were made. Measurements of the newer detectors gave responses to both ^{60}Co and ^{241}Am which were within 3% of the average values for eighteen of nineteen detectors tested. One detector was found to be noisy. The relatively large response seen for 8-5 in Table V and the higher energy of the peak in its ^{60}Co spectrum indicate that the detectors received in the later shipment are thicker than those measured earlier. Comparison of the measured responses with the calculated responses given in Table I indicates a thickness of about 200 μm for the C30808s. With the one excpetion, these detectors were found to have resolutions of about 6 keV (FWHM) at room temperature.

Comparison of measured and calculated responses for the two C30809 photodiodes indicates a thickness of about 250 μm. These detectors, being much larger in area that the C30808s, were found to have resolutions of about 12 keV (FWHM) when operated at 40 V. This is comparable to that of the better ORTEC particle detectors which were measured and which have about the same area.

Table V

Measured Response of RCA Photodiodes Type C30808 (8-1 to 8-5), Type C30812 (12-1) and Type C30809 (9-1 and 9-2) for Ec = 40 keV

Detector #	Applied Voltage (V)	Area (mm^2)	Response (10^7 Counts/(mm^2Gy)) ^{241}Am	^{60}Co Open	^{60}Co (Pb)	Response Ratio $^{241}Am/^{60}Co$ Open	(Pb)	Energy of ^{60}Co Spectrum Valley (keV)	Peak (keV)
8-5	40	8.5	20.7	1.82	1.73	11.4	12.0	47	70
8-4	40	8.5	17.0	1.59	1.52	10.7	11.2	40	61
8-2	40	8.5	16.3	1.52	1.45	10.7	11.2	35	50
8-3	40	8.5	15.8						
8-1	40	8.5	15.7						
8-4	30	8.5	16.5						
8-3	30	8.5	15.4		1.40		11.0	33	53
8-1	30	8.5	15.3						
8-4	20	8.5	15.4		1.45		10.6	35	58
8-3	20	8.5	14.7					23	41
8-1	20	8.5	14.5						
8-2	20	8.5	11.5		1.24		9.3		
8-5	10	8.5	15.3	1.60	1.53	9.6	10.0	37	62
8-4	10	8.5	10.5		1.32		8.0	30	47
8-2	12	8.5	8.5		1.09		7.8	28	36
8-5	5	8.5	11.2	1.45		7.7		33	48
12-1	100	6.6	37	2.62		14.1			(130)
9-1	40	63	25	1.70	1.64	14.7	15.2	45	70
9-2	40	63	23	1.72	1.68	13.4	13.7	47	72
9-2	20	63	22						

Tables VI and VII give detailed responses for detectors 8-2 and 9-2, respectively, for all five sources and for a range of values of E_c. Measured responses are plotted for these two detectors in Fig 4 for E_c = 40 keV. The calculated curves for 100- and 200-μm detectors are shown for comparison. In general, the measured energy response follows the calculated curves, but the measured values for the ^{141}Ce and ^{133}Ba sources are relatively large. This may be due to contributions from scattered radiation. Also, the experimental errors in determining the dose rates from these relatively small sources is fairly large, possibly 20%.

The best energy response for the fully-depleted C30808 and C30809 photodiodes is obtained with 0.4 g/cm^2 tin attenuation and E_c = 50 keV. At this E_c there is a very low response at 140 keV, at least in theory as noted in Ref (2). This could be improved by adding a thin layer of copper or tin as suggested in Ref (2). On the other hand, such non-uniformities in energy response are not important when measuring radiation from a broad spectrum of energies, such as would be encountered from fallout radiation, as shown by the calculations of Hirning (3). An improvement in energy response is obtained by using the C30808 with 10-V bias and E_c = 40 keV. Since operating at partial depletion is not recommended (as discussed elsewhere in this report), a somewhat thinner detector than the C30808 (say 100 or 150 μm as compared with the estimated 200 μm) would result in a more uniform energy response.

The ^{241}Am response of the C30812 detector indicates a thickness of about 400 μm, but the ^{60}Co response is larger than predicted from calculations, as seen by comparison with calculated responses in Table I. This is further evidence of response enhancement resulting from the presence of scattered photons.

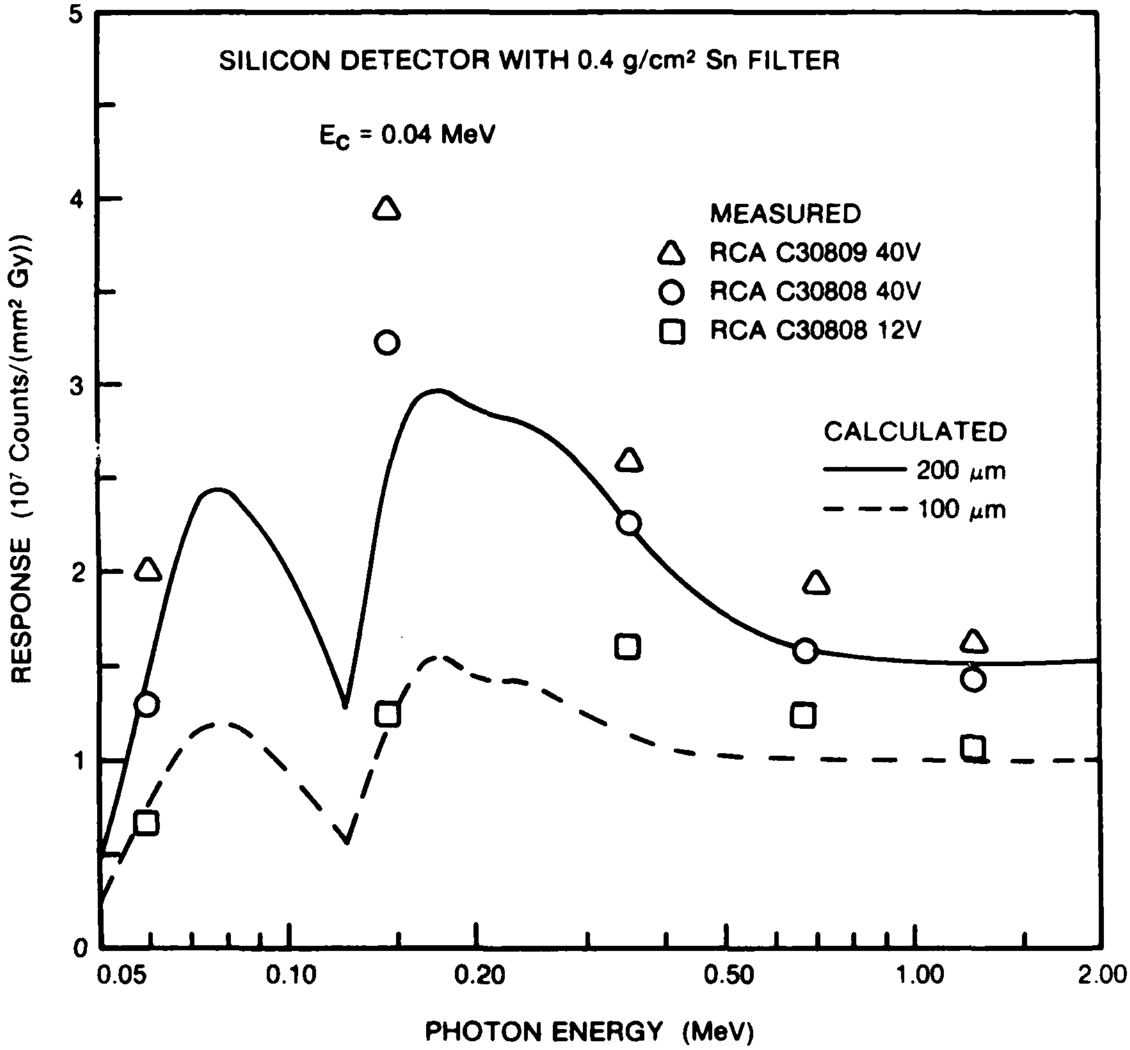

Figure 4. Response of RCA photodiodes as a function of photon energy for the pulse-height discriminator setting of 40 keV. From comparison of measured responses with the calculated curves from Ref (1), the C30808 detector at 40 V appears to have an effective thickness of 200 μm, although the peak in its ^{60}Co spectrum indicates a thickness of 150 μm by comparison of peak energies in Tables V and I. A more unifrom energy response is obtained at E_C = 40 keV with a thinner detector and slightly less photon filtration.

Table VI

Measured Response of Photodiode 8-2 in Units of 10^7 Counts/(mm^2Gy) as a Function of Discriminator Level Ec at Bias Voltages of 40 and 12 V

Source, Energy (MeV)	^{241}Am, 0.06		^{144}Ce, 0.145		^{133}Ba, 0.35		^{137}Cs, 0.66		^{60}Co, 1.25			
Filtration	2mm Al		1/2 mm Cu		2 mm Sn		Pb (÷75)		Open		Pb(÷10)	
Applied Voltage	40	12	40	12	40	12	40	12	40	12	40	12
Ec (keV)												
20	25.0	-	7.42	-	3.05	-	1.85	-	1.75	-	1.66	-
30	19.5	11.4	5.54	2.55	2.65	2.01	1.72	1.42	1.63	1.39	1.55	1.25
40	16.3	8.5	4.01	1.54	2.34	1.66	1.60	1.26	1.52	1.21	1.44	1.09
50	12.7	7.3	2.33	1.31	2.08	1.37	1.48	1.13	1.36	1.03	1.29	0.90
60	4.5	2.7	1.85	0.47	1.86	1.15	1.38	0.99	1.23	0.92	1.16	0.78
80			1.10	0.24	1.35	0.77	1.15	0.78	0.99	0.70	0.94	0.63
100			0.66	0.14	1.12	0.53	0.98	0.62	0.83	0.56	0.80	0.50
125			0.32	0.07	0.85	0.31	0.79	0.45	0.72	0.41	0.69	0.38
150					0.45	0.17	0.63	0.32	0.55	0.30	0.54	0.27
200					0.14	0.03	0.37	0.15	0.36	0.15	0.36	0.14

With Added Filtration of 4 kg/m^2 (0.4 g/cm^2) Sn

Attenuation Factor Used	0.080		0.805		0.970		0.986				0.990	
20	2.00	-	6.00	-	2.96	-	1.82	-			1.64	-
40	1.30	0.68	3.23	1.24	2.27	1.61	1.58	1.24			1.43	1.08
60	0.36	0.22	1.49	0.38	1.80	1.12	1.36	0.98			1.15	0.77
100			0.53	0.11	1.09	0.51	0.97	0.61			0.79	0.50

Table VII

Measured Response of Photodiode 9-1 in Units of 10^7 Counts/(mm^2 Gy) as a Function of Discriminator Level Ec at Bias Voltage of 40 V

Source, Energy (MeV) Filtration	^{241}Am. 0.06 2mm Al	^{144}Ce, 0.145 1/2 mm Cu	^{133}Ba, 0.35 2 mm Sn	^{137}Cs, 0.66 Open	^{137}Cs, 0.66 Pb(÷75)	^{60}CO, 1.25 Open	^{60}CO, 1.25 Pb(÷10)
Ec (keV)							
30	28	7.0	-	-	-	-	-
40	25	4.9	2.67	2.07	1.97	1.70	1.64
50	20	3.1	2.41	1.87	1.82	1.63	1.56
60	10	2.1	2.13	1.75	1.73	1.53	1.50
80		1.40	1.67	1.47	1.50	1.28	1.26
100		0.93	1.31	1.26	1.32	1.10	1.08
125		0.49	0.92	1.02	1.10	0.91	0.92
150			0.56	0.84	0.92	0.77	0.77
200			0.11	0.55	0.62	0.56	0.57

With Added Filtration of 4 kg/m^2 (0.4 g/cm^2)

	^{241}Am	^{144}Ce	^{133}Ba	^{137}Cs	^{60}CO
Attenuation Factor Used	0.08	0.805	0.970	0.986	0.990
40	2.0	3.9	2.59	1.94	1.62
60	0.8	1.7	2.07	1.70	1.48
100		0.75	1.27	1.30	1.07

5. Temperature Effects on Photodiode Performance

The results reported in the above sections of this report are for measurements taken at room temperature (20 to 25°C). Increasing the temperature of semiconductor detectors generally increases the noise level and a detector, which may have no noise pulses above a selected discriminator level E_C at 20°C, may have a signficiant number of noise pulses above E_C at elevated temperatures. These noise pulses would not be distinguished from counts induced by a radiation field so that errors in dose-rate measurement would occur. There is also the possibility that the depleted volume would change with temperature, particularly if the detector is not fully depleted. This would result in a temperature dependence of the detector sensitivity.

No change in sensitivity was observed for a C30807 detector operating at 20 or 40 V over a temperature range of -10 to +50°C. A decrease in resolution from 6 to 8 keV (FWHM) was observed when these detectors were heated from 20 to 50°C. Similarly, no change in sensitivity was found for a C0808 detector operating at 40 V, but about 6% decrease in sensitivity was observed when the same detector, operating at +10V, had its temperature increased from -10 to +50°C. This is an argument for operating these detectors at a bias voltage large enough to fully deplete the detector volume. The C30808 showed about the same decrease in resolution as the C30807 mentioned above. The corresponding increased noise level for these detectors remains small at the elevated temperature (50°C) and there would be no problem using E_C as low as 30 keV. The much larger C30809, however, showed a decrease in resolution from about 12 keV (FWHM) at 20°C to 24 keV (FWHM) at 50°C. This would preclude operation of the C30809 with E_C less than about 50 keV.

6. The Effect of Wall Materials on Response to ^{60}Co

The effect of high-atomic number materials on the enhancement of silicon detector response, at energies where the photoelectric cross section in silicon is relatively large, was investigated in Ref (2). Enhancement of the response at 0.145-MeV, as a result of copper or tin adjacent to the detector, was demonstrated. At ^{60}Co energies, where the photoelectric effect is negligible, the effect of wall materials is more subtle, resulting from differences in the "ratio" of photon-absorption cross section to electron stopping power for different materials. This "ratio" generally decreases with increasing atomic number Z with the result that the fast-electron fluence in materials under photon irradiation is smaller for higher-Z media. Thus, adjacent materials of higher Z than silicon will tend to reduce detector response while lower-Z materials will tend to enhance response to ^{60}Co.

This effect was demonstrated using a C30808 photodiode with the glass window removed and with various materials used adjacent to the detector as the front surface for irradiation. Relative to aluminum, which is next to silicon in Z, Plexiglas and glass were found to increase response to ^{60}Co by approximately 12 and 3%, respectively, while copper was found to reduce ^{60}Co response by approximately 10%. These percentages were essentially independent of the value of E_C used and were not affected appreciably by using the source in the open or attenuated positions. Attenuation effects were accounted for by retaining sheets of both aluminum and the comparison material in the radiation beam and conducting measurements with the order of the sheets in front of the detector changed.

7. Angular Response

The detectors under investigation here are disc-shaped with thicknesses small compared with the range of the secondary electrons produced by high-energy gamma rays such as those from ^{60}Co. This can be expected to give these detectors a response which depends on the direction of the radiation, particularly when the response is measured in terms of counts per unit exposure or per unit dose. In addition, the photodiodes are mounted on the base of transistor cans with different materials adjacent to the front and back surfaces. Both attenuation and differences in wall material can contribute to directional dependence of response.

Response as a function of angle of incidence of ^{60}Co, ^{137}Cs and ^{241}Am photons was measured for the C30807 and C30808 photodiodes and found to be similar for both types and for the C30808 operating at either 10- or 40-V bias. Results are summarized in Table VIII for the C30808 at 40 V for discriminator levels of 40 and 100 keV.

Table VIII

Relative Response as a Function of Angle of Incidence of the Radiation from Three Sources for a C30808 Photodiode with 40-V Bias. 0° Refers to Normal Incidence on the Front (Glass- Window) Surface.

		Angle of Incidence of Radiation						
Source	E_c(keV)	0°	30°	60°	90°	120°	150°	180°
^{60}Co	40	1.00	0.97	0.88	0.79	0.76	0.80	0.82
^{60}Co	100	1.00	0.99	0.94	0.84	0.76	0.75	0.74
^{137}Cs	40	1.00	0.99	0.94	0.86	0.81	0.84	0.865
^{137}Cs	100	1.00	0.995	0.95	0.86	0.78	0.80	0.80
^{241}Am	40	1.00	0.98	0.72	0.60			0.31

Increasing the angle to the normal (from both the front and back is seen in Table VII to give a small decrease in response for both ^{60}Co and ^{137}Cs photons. From the front, this partly results from a larger fraction of larger pulses as the angle is increased. Attenuation of about 3% is estimated for ^{60}Co and ^{137}Cs photons at 180°. The larger part of the response reduction for irradiation by these sources from the back is due to differences in wall materials as discussed in Sec. 6.

For the ^{241}Am source attenuation at 180° is seen to reduce response by a factor of about three. This is less than the attenuation at this energy required to give optimum energy response. The 0.4 g/cm^2 of tin used for Figs 3 and 4 reduce the response for ^{241}Am photons by a factor of about twelve. Thus, the photodiode package could be incorporated along with the filtration required to give good response over the photon energy range of interest.

8. Degradation of Detector Response as a Result of Exposure to Neutrons

Silicon diodes used as the detector in military dose-rate instruments may be subjected to neutron irradiation during a nuclear-weapon burst. The resulting displacement damage could result in degradation of performance in subsequent use of these detectors. As a measure of this effect, two of the RCA C30807 photodiodes were exposed to neutrons from a ^{252}Cf source. The sensitivities after exposures of approximately 5 and 10 Gy were compared with the pre-irradiation values for the diodes under both fully-depleted and partially-depleted conditions. The measured sensitivities are given in Table IX for E_c = 40 keV.

TABLE IX

Measured Sensitivities of Two RCA C30807 Photodiodes before and after Exposure to Neutrons from a ^{252}Cf Source.

Detector #	Bias (V)	Measured Sensitivity (10^7 Counts/(mm^2 Gy) Pre-Irradiation	After 5 Gy	After 10 Gy
8	40	16.0	15.0	14.4
11	40	14.5	14.3	13.7
8	15	11.5	8.8	8.3
11	10	11.0	8.4	7.7

Under fully-depleted conditions (40 V) the average reduction in sensitivity for the two diodes is 4% and 7% for 5 and 10 Gy, respectively. At the lower bias voltages, these reductions are increased to 24% and 29%. The resolution of these detectors remained at about 5 keV (FWHM) after the irradiations. The larger decreases in sensitivity at the lower biases is probably due to a decrease in the depleted detector volume. These doses are, or course, larger than the operator of a radiation instrument could tolerate, but it is conceivable that the instrument could be exposed and used at a later time by an operator from a more sheltered location. It can be concluded that it is good practice to operate these detectors at bias voltages which are at least large enough to ensure that they are fully depleted.

9. Summary and Conclusions

Measurements of the radiation response of some Ortec particle detectors and RCA photodiodes show general agreeement with computer calculations made using a radiation-transport code where source energy and geometry conditions are well enough defined to make direct comparisons. Factors, which produce minor deviations from conditions used for earlier calculations, include the presence of scattered photons and the detector mounting.

The response to the higher energy sources (^{60}Co and ^{137}Cs) were found to be enhanced (by about 10% for E_c = 40 keV) when used as open sources in comparison to attenuated operation. This is attributed to the presence of backscattered photons in the energy range of 200 keV. The response to the ^{141}Ce source can be very dependent on radiation scattering which accounts for the fact that most of the measured responses are greater than the calculated values for that energy, assuming detector thicknesses based on responses at other energies.

Measurements with ^{60}Co demonstrated the effect of changing the atomic number of material in front of the detector. Replacing aluminum with copper immediately in front of a C30808 detector, with the glass window removed, reduces the response by about 10%, while Plexiglass increases the response by about 12%. This effect is probably responsible for much of the variation in photodiode response with direction of the radiation for the higher energy photons.

The sensitivity of the C30808 photodiode (approximately 10^8 counts/Gy or 300 (count/s)/(cGy/h)) makes it suitable as the detector in military instruments for measuring high dose rates. By carefully selecting photon filtration and pulse-height discriminator level, energy response can be achieved which is sufficiently uniform to give a good measurement of the gamma radiation from fallout. However, indications are that good energy response could be more readily achieved using a somewhat thinner detector than the C30808. The C30808 and C30807 photodiodes make high quality detectors for ionizing radiation and can be used at discriminator levels of 30 keV at elevated (50°C) temperatures.

It has been shown that these detectors undergo damage by neutron irradiation, but the effect is not large in an environment in which troops could survive. The effect is minimized by operation at biases which fully deplete the detector volume.

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This report gives the results of measurements of the response of some commercial photodiodes and particle detectors to monoenergetic gamma-ray sources. The absolute response and the response, as a function of photon energy, detector thickness and discriminator level, were investigated and are shown to be in general agreement with earlier calculations. It is concluded that, with appropriate photon filtration, the small photodiodes tested would be suitable for the relatively high dose-rate measurements of primary interest for military applications, although their thickness is greater than the thickness for best energy response.

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Silicon Detector

Gamma Radiation

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